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Dynamics of Annular Variability (Extended Abstract)

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Annular variability is the variation expressed in temporal anomalies of zonal averages of wind, temperature and pressure. In the Southern Hemisphere, the dominant modes of variability are nearly zonally symmetric, so that annular variability is the most important type of variability on long time scales. Diagnosis of observations indicate that the zonal flow variations are driven by anomalies in the momentum transport by synoptic mid-latitude eddies and their interaction with zonal flow (Yoden *et al.*, 1987, Hartmann 1995, Hartmann and Lo 1998). This type of annular mode of variability is readily produced in simple models of the atmosphere (Robinson 1991, James and James 1992, Yu and Hartmann 1993, Akahori and Yoden 1997). In the Northern Hemisphere, the tradition has been to define regional modes of variability such as the North Atlantic Oscillation and the Pacific-North America Pattern, but recently it has been argued that the dominant mode of Northern Hemisphere variability may also be fundamentally zonal (Thompson and Wallace 1998, Wallace 2000).

The annular modes of variability in both the Northern and Southern Hemispheres can be simulated extremely well by general circulation models such as that of the Geophysical Fluid Dynamics Laboratory (GFDL) (Limpasuvan and Hartmann 1999, Limpasuvan and Hartmann 2000). This allows a careful analysis of the dynamics of the modes to be completed. In addition, since the simulation has specified, seasonally varying sea surface temperature (SST), the annular variability must come entirely from the internal dynamics of the atmosphere. That the model produces not only the structure, but also the amplitude of the annular variability suggests that this variability is not heavily dependent on SST anomalies for its existence. We therefore must conclude that the annular modes are unforced internal modes of variability of the atmosphere.

The dynamical maintenance of the annular modes in the GFDL model is consistent with observational studies. In the Southern Hemisphere the annular mode results from a strong interaction between the zonal mean flow and eddy momentum fluxes produced by transient, synoptic-scale eddies. In the Northern Hemisphere the primary support for the zonal-mean momentum anomalies is from momentum transports by quasi-stationary planetary-scale waves. Studies have suggested that the zonal flow anomalies associated with the northern annular mode produce changes in planetary wave structure that, in turn, produce anomalies in planetary-wave momentum flux that act to sustain the zonal-wind anomalies (DeWeaver and Nigam 2000b, DeWeaver and Nigam 2000a). Thus the southern and northern annular modes are both internal modes of variability, but stationary waves are central in the north and transient waves are central in the south.

In the Northern Hemisphere the zonal-flow anomalies extend upward into the stratosphere during the winter half year (Thompson and Wallace 2000). The annular structures in both the troposphere and stratosphere project strongly onto patterns of change over the last 30 years. It is interesting to understand the reasons for this correspondence between troposphere and stratospheric trends over the last 30 years. Data suggest strong changes in planetary wave structure and planetary wave propagation into the stratosphere associated with the northern annular mode (Hartmann, *et al.* 2000). Part of this change may be due to changes in the propagation characteristics of planetary waves, which are sensitive to wind shear near the tropopause (Chen and Robinson 1992, Limpasuvan and Hartmann 2000). In addition, the changed tropospheric winds may alter the magnitude or wavenumber of the resulting planetary waves. Hartmann *et al.* (2000) show that the upward energy flux is not sensitive to the northern annular mode polarity, but that the upward wave activity flux shifts from wavenumber-1 to wavenumber-2 when the winds shift poleward in the troposphere and the stratospheric jet is correspondingly stronger. Since wavenunber-2 propagates less readily into the polar region, these two changes are consistent with wave, mean-flow interaction theory. Stronger winds at high latitudes produce a shift to wavenumber-2 which tends to bend equatorward, rather than propagate into and disrupt the high latitude jet.

Annular variability in the troposphere and stratosphere are strongly coupled, particularly in the Northern Hemisphere during late winter and spring seasons. The strength of this coupling is related to planetary wave propagation. The upward influence of the troposphere on the stratosphere is well understood in terms of linear wave dynamics and wave, mean-flow interaction. Considerable evidence also exists to suggest that stratospheric zonal flow variations can affect tropospheric flow. The theory for this is less well developed. We use the 40-year NCEP record to study annular coupling in the Northern Hemisphere during winter. The dynamical connection between tropospheric and stratospheric annular modes of variability suggests a strong likelihood of synergism between changes produced by greenhouse gas increases and changes caused by stratospheric ozone depletion.

Since the annular modes are free modes of variability, they may respond with larger than expected changes to modest forcing of the climate. Both ozone depletion and greenhouse gas increases yield enhanced meridional temperature gradients and enhanced vertical shear near the tropopause in high latitudes, which should refract planetary waves toward the tropics. This suggests that a cooling of the polar stratosphere and a reduction in stratospheric warmings should accompany both ozone depletion and greenhouse gas warming. Thus, recent large trends in the northern annular mode polarity may be a result of synergy between greenhouse gas effects and ozone depletion effects on the polarity of the northern annular mode (Shindell *et al.*, 1999, Hartmann *et al.*, 2000). Though these forcings are weak, because the annular mode is a free mode in the troposphere, larger than expected changes in surface climate can be produced by weak forcing applied in either the troposphere or stratosphere. Greenhouse warming and ozone depletion seem to push the northern annular mode polarity in the same direction, toward a more cyclonic polar circulation, with reduced occurrence of midwinter stratospheric warming. The effects of these changes are particularly strong in the Arctic, where the trends are toward more cyclonic circulations and reduced sea ice (McPhee *et al.*, 1998, Rothrock *et al.*, 1999).

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